第 37 卷第 14 期 生 态 学 报 Vol.37,No.14
2017 年 7 月 ACTA ECOLOGICA SINICA Jul.,2017

DOI: 10.5846/stxb201603310588
鲍林林,李叙勇,苏静君.筑坝河流磷素的迁移转化及其富营养化特征.生态学报,2017,37(14):4663-4670.
Bao L L, Li X Y, Su J J.Phosphorus cycling and the associated ecological effects of eutrophication in dam-regulated rivers.Acta Ecologica Sinica,2017,37(14):4663-4670.

筑坝河流磷素的迁移转化及其富营养化特征

鲍林林[1,2],李叙勇[1,*],苏静君[1]

1 中国科学院生态环境研究中心,城市与区域生态国家重点实验室, 北京 100085
2 中国科学院大学, 北京 100049

摘要:人类活动过量营养物质输入是导致河流富营养化的主要原因,而河道过度的人为调控则进一步复杂化了河流的营养状态变化。闸坝是河流人为调控的重要工程措施之一,提高水资源利用效率的同时严重干扰了河流自然的生物地球化学循环,产生诸多负面生态环境效应。磷素的迁移转化对河流的营养限制作用受到越来越多的关注,国内外已有研究在筑坝河流磷的富营养化特征方面,已经取得了较为深刻的认识:水库闸坝建设滞留大量磷素,导致河流水体磷含量升高、营养物质比例变化,沉积物储存过量磷素形成的内源释放威胁,以及进一步浮游植物和有害藻类的生长响应等,使得筑坝河流的富营养化生态风险升高;在此基础上,也提出了根据降雨分配和闸控库区储水,合理设置闸坝泄流方式,以改善筑坝河流富营养化生态风险的重要管理思路。对于闸坝调控作用与水体富营养化的定量关系还有待进一步的探讨,而且随着河流资源开发和人为调控力度的增强,河流闸坝建设所产生的系列生态环境问题日益严峻,对此提出还需要系统研究的方向:闸坝调控作用下河流磷素的富营养化机制及其与氮、碳等元素的耦合作用,筑坝河流沉积物内源污染的综合管理,以及闸控景观河流的生态建设和修复等。

关键词:筑坝河流;磷滞留;富营养化;沉积物;闸坝泄流

Phosphorus cycling and the associated ecological effects of eutrophication in dam-regulated rivers

BAO Linlin[1,2], LI Xuyong[1,*], SU Jingjun[1]

1 *State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing* 100085, *China*
2 *University of Chinese Academy of Sciences, Beijing* 100049, *China*

Abstract: The anthropogenic input of nutrients to rivers is the main cause of eutrophication, and both the excessive control and engineering of river channels further complicate the issue. To meet the demand for energy and water resources, thousands of dams, weirs, and sluices have been constructed and affected almost every river, which deeply interferes with the biogeochemistry cycles of nutrients and the ecological function of river systems. Previous research has investigated the ecological effects of eutrophication caused by phosphorus in dammed rivers, since phosphorus limitation of primary production is more predominant in river systems. Dammed rivers can reduce outflow and, hence, sequester a significant amount of phosphorus within the impoundments. As a consequence, river water becomes eutrophic, and the ratios of main nutrients change drastically, owing to the different responses of the nutrients to retention by dams. In addition, sediments in the dammed rivers, which containing high contents of phosphorus, can easily become a potential pollution source, especially under intensive scouring events. At the same time, the abundance of algae communities increases, as certain

基金项目:京津冀城市群地区生态安全关键技术综合示范区建设(2016YFC0503007);国家水体污染控制与治理科技重大专项(2015ZX07203-005);中国科学院重点部署项目(KZZD-EW-10-02);国家自然科学基金青年基金(41401590)

收稿日期:2016-03-31; **网络出版日期**:2017-03-02

* 通讯作者 Corresponding author.E-mail: xyli@ rcees.ac.cn

species bloom in the water column, which aggravates the ecologic effects of river eutrophication and threatens the biodiversity of river systems. Therefore, researchers have found that an efficient management strategy based on annual rainfall storage and dam discharge control can be used to improve the ecological effects of eutrophication in dammed rivers. However, as anthropogenic impacts continue to increase, further studies of dammed rivers are needed to clarify the relationship between artificial control in rivers and river eutrophication, in order to reduce the ecological effects of eutrophication, as well as to quantify the threshold of phosphorus, in order to further understand the eutrophication mechanisms of dammed rivers and the combined effects of nitrogen and carbon, to manage phosphorus within sediments, in order to prevent its release and resuspension, and to address concerns regarding the construction and restoration of landscape rivers with dams throughout China.

Key Words: dammed rivers; phosphorus retention; eutrophication; sediment; reservoir discharge

如今,水体富营养化现象已经成为全球化的环境问题[1-3],而过量营养物质向河流、湖泊和海岸带等的输送,是导致其富营养化的主要原因[4-5]。作为生态系统重要的生源要素之一,磷素在河流和湖泊等淡水生态系统的营养限制性作用逐渐凸显,并成为控制水体富营养化和有害藻华爆发的关键[6]。河流是陆地与海洋生态系统之间物质循环的桥梁,人类活动的增强加速了流域内大量资源性磷素活化和流失[7],使得水体的磷负荷和富营养化趋势急剧增加,河流生态系统功能也逐步退化[8-9]。然而,高强度的人为调控对河流形态的改变,如闸坝水库修建、河道渠道化、地下水过度开发以及引调水等,进一步加剧了河流的富营养化生态风险[10-11]。

闸坝是河流人为调控的主要工程措施,以满足人类获取能源、防止洪涝、提高灌溉和改善通航等各种需求,但另一方面,筑坝使河流逐渐"湖库化",将强水动力条件下的河流搬运作用,逐渐演变为弱水动力条件下的湖泊沉积作用;根据国际大坝委员会(ICOLD)的记录,中国是世界上大型闸坝(坝高≥15 m)建设最多的国家,加上不计其数的小型闸坝、堰坝和橡胶坝,其对河流生境破坏和水质影响难以估量[12]。闸坝不仅阻滞了河流的水力循环,更是强烈的扰乱了河流原有的物质场、能量场、化学场和生物场,进而改变河流生态系统的物种组成、栖息地分布以及相应的生态功能[13]。对于河流磷素的迁移转化,闸坝的拦截,使得水体滞留时间增加,磷素等营养物质积累,更加有利于浮游植物生长,进而也加剧了河流水体的富营养化趋势[14-15]。所以,关于闸控型河流磷素的迁移转化和相应的水体富营养化趋势的变化特征,以及河流生态环境改善的理论和实践研究都具有重要意义[16-17]。

由此,本文主要针对国内外筑坝河流磷素迁移转化及其富营养化的相关研究,总结了闸坝调控下河流对磷素的滞留特征,水体的营养物质分布、浮游植物生长响应和沉积物蓄积磷素的内源污染,以及闸坝泄流水力调控作用下的富营养化生态风险改善等。较为全面的梳理了目前对筑坝河流磷循环和闸坝调控干扰的认识,并提出了应着重开展闸控河流的富营养化机制、合理控制沉积物内源负荷、解决闸控景观河道富营养化所产生的系列生态问题的研究展望和应用,为我国普遍存在的筑坝河流的生态建设和管理提供参考。

1 河流磷素来源和迁移转化特征

磷是生命活动必须的营养物质之一,河流生态系统的磷素包括自然来源与人为来源,但是由于经济发展和城市化的不断深入,人为来源磷素显著的增加了河流的磷负荷和污染程度[7-8]。其中,由人类活动所产生的磷素,主要来自于生活污水和工业废水为主的点源排放,以及农业和城市产生的非点源输入[18-20],而且,降雨径流冲刷驱使的非点源磷流失常以颗粒态磷为主,高度集中的点源排放则主要为溶解态活性磷(SRP),点源溶解态磷对河流磷浓度、沉积物磷负荷的贡献,也常常是导致水体富营养化的主要原因[21]。可见,流域内气候环境和人类活动特征的影响是河流磷素的来源、形态和分布的关键因素,特别是 SRP 的输入,其具有较高的生物可利用性[22-23],容易诱发浮游植物爆发性生长并逐步恶化水生态环境[24-25]。

磷素在河流内部的迁移转化,主要包括生物循环、沉积物吸附释放和悬浮物迁移等过程(图 1)[8]。不同的循环过程决定了磷的形态、分布和生态环境效应。这些物理、化学、生物过程的相互作用对流域磷素的输入输出也具有一定调节作用。研究表明,每年大概有30%的 SRP 滞留在 Walker Branch 流域(美国)的河道内[26],并主要由生物吸收所去除[8]。多样化生物群落(包括浮游植物、大型植物、动物和微生物等)的吸收利用和释放能够有效削减和缓冲水体磷负荷,并维持河流良好的生态系统服务功能,但是单一种类的生物爆发性生长则适得其反。沉积物的吸附和释放是缓冲上覆水体中磷含量和形态分布的主要过程。沉积物吸附沉积,能够降低水体磷浓度,而沉积物的磷释放、矿化则能够继续维持水体磷需求,甚至提高水体富营养化程度。悬浮物对磷素的吸附、释放和迁移作用,也关系到河流水体及其下游受纳水体的磷浓度和营养水平。据估算,英国有 26%—75%的磷素是由河流悬浮物输送到海洋中[27],Seine River(法国)河口的磷通量结果也表明悬浮物的迁移作用约占总磷(TP)的 44%[28]。可见,悬浮物是陆源磷素输出的重要介质[29],当然,悬浮物沉降将磷素转移到河床沉积物中时,也可以一定程度的降低水体磷含量[30]。总之,河流磷素来源和迁移转化规律,关系到水环境中磷素的最终归宿和受纳水体的营养状态,对于掌握河流生态系统磷循环、控制流域富营养化至关重要。而闸坝建设等人为调控对河流磷循环的干扰作用,对深入理解现如今河流的磷素迁移转化特征和水体富营养化响应更加具有现实意义。

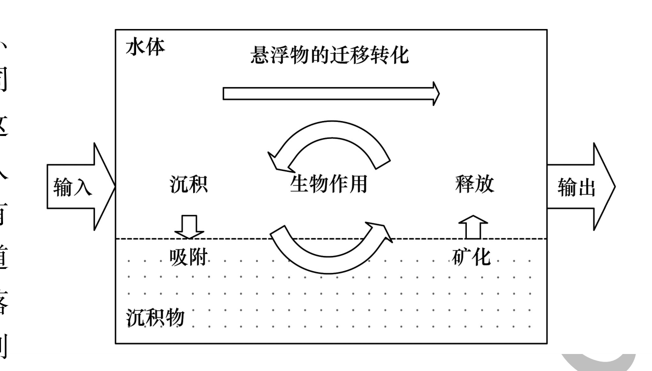


图 1　河流内部磷素迁移转化的主要过程

Fig.1　In-stream processes of phosphorus cycling and delivery

2　闸坝建设对河流磷素迁移转化的影响

2.1　闸坝拦截下河流磷滞留特征

人类活动极大的改变了全球磷循环,闸坝的建设使得河流磷素的迁移转化、滞留特征和相应的生态效应变得更为复杂[31]。筑坝河流具有大面积稳定水域(如水库),减少了河流水量输出的同时截留大量营养物质[32],所以大大提高了磷滞留能力,而且,从全球范围看来,河流的磷滞留量会随着库坝建设的扩张而持续升高[31]。研究表明,Seine River(法国)上游流域库坝滞留了 60%的入库磷酸盐,主要被沉积物和底栖生物所吸收[33];美国中西部河网闸控河段和自然河段长年监测数据的对比分析表明,水库出水比无闸坝拦截河流出水的 TP 年输出量减少约 20%,TP 输出的年内变化也因闸坝的调控而变小[11]。磷素的大量滞留,使得筑坝河流的磷含量显著升高[34],闸坝出水磷浓度相对较低,这对农业流域排水河道来说,筑坝可以有效地减少磷素等污染物质的输出,具有流域污染最佳管理措施的功效[35]。此外,对于营养物质含量本身较低的河流来说,闸坝拦截使得滞留水体营养水平升高的同时可能还会引起下游水体的贫营养化。比如,Luleälven River(瑞典,欧洲闸坝调控最严重的河流)沿程众多闸坝水库的建立导致该流域磷的输出逐渐减少[36-38],威胁到海岸带的初级生产力[39-40]。

河流梯级开发的闸坝建设对水量和营养物质的截留强度更甚。由于高强度的梯级开发,黄河流域的断流和水质恶化现象愈加严重,TP 的输出减少了 84%左右[41];长江上游流域也建设有大量的闸坝和水库,尤其是三峡大坝建设后,其向中下游流域输送的 TP 减少了 77%[42];猫跳河是中国第一条被完整开发的河流,是全国流域梯级开发最早和程度最高的河流,全流域水能资源控制近 90%[43],其系列水库对磷的逐级滞留,使得磷酸盐浓度降低了约 90%[17,44]。总之,闸坝这一强有力的人为调控方式,改变了河流营养物质的循环和分布,导致滞留水体的磷含量升高,提高筑坝河流的营养水平,引发其富营养化,而其下游水体的营养状况因磷输出减少而有所降低,甚至加剧贫营养化从而限制初级生产力。可见,闸坝的磷滞留能力关系到筑坝河流及其下游水体营养状况,对整个生态系统都具有深远的影响。

2.2 筑坝河流磷素的富营养化特征

2.2.1 磷含量升高和营养物质比例变化

大量磷素有效拦截和水体较长的滞留时间都为浮游植物生长提供了有利的条件,筑坝河流的富营养化问题更加严峻[5,45]。Han River 是韩国最重要的河流,其主干和支流建立有各种水库大坝、堤坝、浸没式闸坝、小型堰坝等,导致河道磷素大量滞留,浮游植物常爆发性生长[46-48]。澳大利亚西南部的 Canning River 和 Lower Vasse River,春末到秋初整个生长季节河流处于拦截蓄积状态,水体的 TP 浓度升高,大型水生植物逐渐消失,浮游植物成为优势类群并大量生长[49]。进一步水质恶化会使筑坝河流的生物多样性降低,生态系统功能急剧退化。另一方面,闸坝内滞留水体营养物质的拦截和浮游植物吸收利用,可以一定程度降低下游水体浮游植物的生物量和爆发风险[44,50],但是,当遇到大规模降雨或洪水事件,储存在坝内的营养物质和浮游植物被冲刷流出时,下游水体将受到严重污染[50]。

营养物质含量升高导致浮游植物大量生长是河流富营养化最直观的表现,所以,营养物质含量与浮游植物群落特征的响应也能反映水体营养状况的变化特征。研究表明,水体浮游植物爆发性生长,主要是少数藻类优势生长的结果,营养物质的过量输入更加有利于单一类群的有害藻类大量生长[10]。所以,闸坝滞留水体中的藻密度通常高于自然河流段,而藻群结构的丰富度较低[51],其优势类群也主要为喜营养丰富和静水环境的种类(如绿藻)[52]。闸坝的拦截作用还会引起主要营养物质,如氮(N)、磷(P)和硅(Si)比例的变化,对水体富营养化和藻群结构变化也具有显著影响作用。由于硅的沉降效率较高而磷素的循环速度相对较快,筑坝使得河流 Si∶P 比例明显降低,Danube River(法国)即因系列闸坝调控,河流湖库化营养物质比例失衡,甲藻类有害藻类大量生长,导致海岸带渔业受到严重影响[10]。猫跳河的梯级水库中上游库区磷素大量滞留时,为绿藻和蓝藻等优势种类所利用[53],下游水库磷含量降低时,Si∶P 比例有所升高,所以浮游植物中硅藻的比重又有所增加[44]。相对于水体流动性和连续性较好的自然河流,筑坝河流的营养物质比例和藻群结构常发生显著变化[54-55],从而改变其富营养化特征。已有研究表明,由于河流闸坝滞留相当量的营养物质(特别是 Si 和颗粒态的 N、P),而人类活动产生的溶解态 N、P 却有增无减,河流输出 Si∶N∶P 比值持续下降,这将会导致我国主要海域非硅质浮游植物和有害藻类的持续爆发性生长,危害整个水环境安全和人类健康[2,40,56]。总之,闸坝的水力拦截使得河流的富营养化生态风险急剧升高,从生态恢复的角度来解决这一问题将具有非常大的挑战。

2.2.2 沉积物内源磷释放的污染

筑坝河流更容易淤积大量沉积物,成为磷素主要储存库,特别是颗粒态磷和悬浮物携带的磷素更容易储存在坝内沉积物中[42],使其成为筑坝河流富营养化的主要污染源之一。已有研究表明,城市河流 Tanchun Stream(韩国)拦蓄河段内沉积物中的 TP 含量和沉积物的磷释放潜力均显著高于其下游河段,对滞留水体的富营养化具有很大贡献[46];1997—1998 年夏季,由于 Canning River(澳大利亚)的拦蓄滞留,沉积物释放大量磷素,导致河流爆发蓝藻而不得不停止向公众开放[57];Lot River(法国)系列闸坝库区的沉积物中曾储存有近 10 000 t 的生物可利用磷素[58],澜沧江梯级水库内沉积物的生物可利用磷含量也非常高,具有很高的释放风险和生态威胁[59-60];九龙江北溪西坡电站库区的沉积物则已经处于磷释放状态[61]。而且,洪水爆发等所致河流水动力增强时,筑坝河流沉积物中的磷素也会因冲刷再悬浮作用而释放出来,对水体造成二次污染[50,62]。可见,沉积物对磷的吸附与释放,是控制筑坝河流水体富营养化和维持滞留水体自净能力的关键[63],河流的闸坝建设也需要关注沉积物内源磷释放的污染问题。

3 闸坝水力调控的富营养化生态风险改善

控制人类活动过量营养物质的输入,能够有效降低河流生态系统的磷负荷和富营养化趋势,而对于筑坝河流来说,改善磷素的富营养化生态风险还需要从优化闸坝调控等方面着手,因为河流水体滞留容易引发富营养化,而一定强度的水动力扰动则不利于营养物质滞留和浮游植物爆发性生长[64-65]。

位于韩国东南地区的 Nakdong River(韩国第二大河)建设有 4 个多功能水坝和 1 个河口大坝以调控整个流域的流量,水体富营养化严重,常有浮游植物爆发性生长,而且季风和台风所产生的降雨年际分配不均也是导致河流水量、水质年际变化的原因之一。所以,Jeong 等[15]根据降雨、流量和闸控泄流等与水体叶绿素含量的响应关系,提出了通过多年自然降雨状况,调控闸坝泄流方式和泄流流量,以缓解河流的富营养化趋势并改善水质。其调控方式如图 2 所示,如果当年和上一年雨季都有足够降雨,库坝内水量充足,则增加闸坝泄流量,如果两年中只有一年降雨充沛,则需要谨慎管理坝内储水,采用脉冲式泄流,这两种情景都能改善筑坝河流的富营养化状况,抑制浮游植物生长;但是,如果连续两年没有充沛降雨,蓄水不足,闸坝泄流将减少,浮游植物爆发性生长则不可避免。闸坝泄流的冲刷和稀释作用,能够显著降低下游河段的氮磷浓度,并且减少水体中藻群的生物量[66],这种根据水量分配以控制闸坝泄流的方式,对于河流年际的水质改善和枯水期的水质改善都具有积极作用[67]。

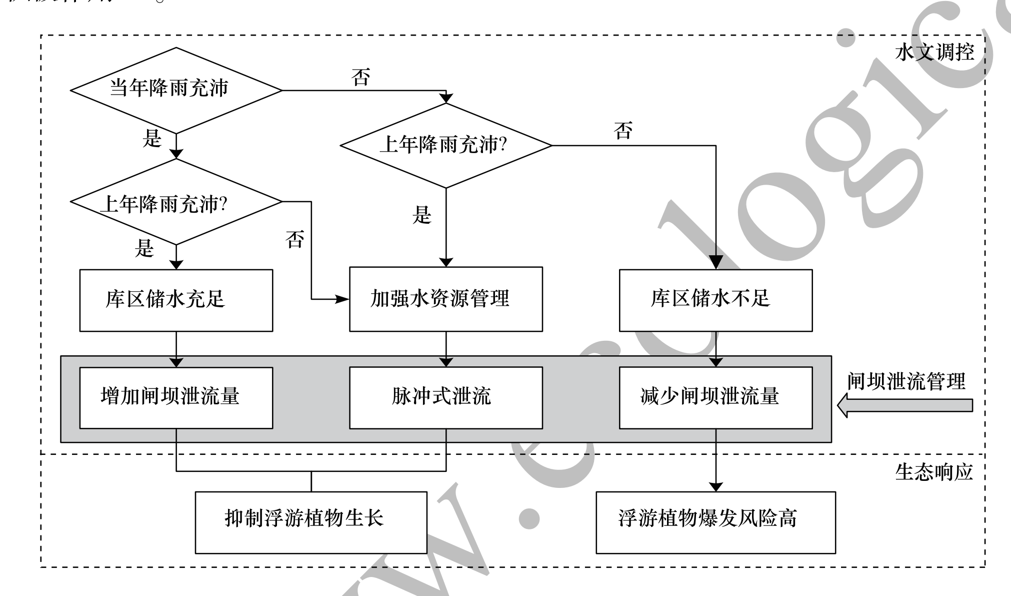


图 2　根据气候变化和浮游植物繁殖特征的筑坝河流水文管理示意图[15]

Fig.2　Diagram depicting the river regulation mechanism regarding climate changes and phytoplankton population dynamics

闸坝泄流调控的作用在于:适当的泄流量可以防止水体长期滞留形成温度分层,而且较高的流速能够增加浊度以减少光的可利用性,同时稀释和转移藻类细胞,从而有效地抑制单一藻类和有害藻类的大量生长,以达到改善水质的目的[68-69]。Webster 等[70]也认为,从优化闸坝泄流方式出发,采用闸坝最小基本泄流流量、脉冲式泄流、高落差泄流、虹吸式泄流等水力调控措施,均能降低闸控滞留水体和下游水体的富营养化生态风险。此外,Alrajoula 等[71]的研究表明,闸坝调控的水动力变化在汛期具有积极作用,但是枯水期的流量干预对下游河流生态系统具有一定负面影响(如岸边栖息地的扰动),可见,闸坝泄流的有效管理和实践应用还有赖于对流域降雨、闸坝储水、泄流量的时空分配和水质变化、生态效益之间响应关系的定量化研究[72]。当然,如今人类活动对生态系统的干扰有增无减,气候变化所致降雨分配变异也越来越大,筑坝河流的富营养化生态风险改善和生态恢复将是成效缓慢且需要持续关注和巨大投入的漫长过程。

4　结论与展望

综合看来,闸坝建设对河流磷素分布和富营养化的影响已经取得了较为充分的认识,闸坝建设使得磷素大量滞留加快了水体的富营养化趋势,由此导致河流营养物质的迁移输出比例失调,浮游植物爆发风险升高,而沉积物富集磷素的内源释放污染也具有很大威胁。如何有效地改善闸坝滞留磷素的富营养化生态风险,以及合理科学的控制闸坝运营方式,是目前筑坝河流生态环境建设和管理亟待解决的问题。在此基础上,筑坝河流的富营养化还需要进一步关注以下几个问题:

（1）河流磷素的富营养化机制及其与氮、碳等其他元素的耦合作用　磷的形态决定了其生物可利用性和滞留方式，及其与浮游植物生长的响应关系，筑坝河流的富营养化还受到流量、水体滞留时间和闸坝泄流等水力条件的影响作用，此外，水体富营养化是包括了碳源和氮、磷等营养物质供给和环境变化响应的综合过程[45]，所以，筑坝河流人为调控作用下不同形态磷的迁移转化和相应浮游植物生长的营养物质阈值的定量分析，以及磷与碳、氮耦合对水体富营养化的影响作用，对阐明筑坝河流的富营养化机制具有重要意义，有待进一步的研究解答。

（2）沉积物内源污染的综合管理　闸坝拦截有效滞留大量磷素和沉积物，导致相当部分的磷素蓄积在坝内沉积物中，而沉积物的磷吸附释放直接关系到滞留水体的营养状况和水质安全。控制外源磷污染的同时，内源磷释放的管理是筑坝河流需要特别重视的问题，清淤、锁磷剂固持以及沉水植物种植等方法，都对沉积物内源释放具有一定的改善效果，但是具体控制管理措施的实施和评估，还需要结合筑坝河流沉积物的吸附释放特征不断地尝试和改进。

（3）闸控景观河流的生态修复　河道景观化是目前我国河流综合整治和管理的主要方式之一，特别是在城市黑臭河道的整治方面。但是，硬质化河床和护坡以及一系列长期处于闭蓄状态的闸坝或橡胶坝的设置，导致景观河流水质依旧不容乐观，水体富营养化严重、河道自净能力低、河流生态功能简单化等。景观河流的建设和管理更应该关注筑坝所带来的水体富营养化等负面生态效应，以达到真正的河流景观建设和生态环境恢复。

参考文献（References）：

[1] Smith V H. Eutrophication of freshwater and coastal marine ecosystems: a global problem. Environmental Science and Pollution Research, 2003, 10(2): 126-139.

[2] Strokal M, Yang H, Zhang Y C, Kroeze C, Li L L, Luan S J, Wang H Z, Yang S S, Zhang Y S. Increasing eutrophication in the coastal seas of China from 1970 to 2050. Marine Pollution Bulletin, 2014, 85(1): 123-140.

[3] Conley D J, Paerl H W, Howarth R W, Boesch D F, Seitzinger S P, Havens K E, Lancelot C, Likens G E. Controlling eutrophication: nitrogen and phosphorus. Science, 2009, 323(5917): 1014-1015.

[4] Hilton J, O'Hare M, Bowes M J, Jones J I. How green is my river? A new paradigm of eutrophication in rivers. Science of the Total Environment, 2006, 365(1/3): 66-83.

[5] Tekile A, Kim I, Kim J. Mini-review on river eutrophication and bottom improvement techniques, with special emphasis on the Nakdong River. Journal of Environmental Sciences, 2015, 30: 113-121.

[6] Elser J J, Bracken M E S, Cleland E E, Gruner D S, Harpole W S, Hillebrand H, Ngai J T, Seabloom E W, Shurin J B, Smith J E. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters, 2007, 10(12): 1135-1142.

[7] Filippelli G M. The global phosphorus cycle: past, present, and future. Elements, 2008, 4(2): 89-95.

[8] Withers P J A, Jarvie H P. Delivery and cycling of phosphorus in rivers: a review. Science of the Total Environment, 2008, 400(1/3): 379-395.

[9] Jarvie H P, Jürgens M D, Williams R J, Neal C, Davies J J L, Barrett C, White J. Role of river bed sediments as sources and sinks of phosphorus across two major eutrophic UK river basins: the Hampshire Avon and Herefordshire Wye. Journal of Hydrology, 2005, 304(1/4): 51-74.

[10] Friedl G, Wüest A. Disrupting biogeochemical cycles-consequences of damming. Aquatic Sciences, 2002, 64(1): 55-65.

[11] Powers S M, Tank J L, Robertson D M. Control of nitrogen and phosphorus transport by reservoirs in agricultural landscapes. Biogeochemistry, 2015, 124(1/3): 417-439.

[12] Rosenberg D M, McCully P, Pringle C M. Global-scale environmental effects of hydrological alterations: introduction. BioScience, 2000, 50(9): 746-751.

[13] 毛战坡，王雨春，彭文启，周怀东. 筑坝对河流生态系统影响研究进展. 水科学进展，2005，16(1)：134-140.

[14] Chen N W, Hong H S. Integrated management of nutrients from the watershed to coast in the subtropical region. Current Opinion in Environmental Sustainability, 2012, 4(2): 233-242.

[15] Jeong K S, Kim D K, Joo G J. Delayed influence of dam storage and discharge on the determination of seasonal proliferations of *Microcystis aeruginosa* and *Stephanodiscus hantzschii* in a regulated river system of the lower Nakdong River (South Korea). Water Research, 2007, 41(6): 1269-1279.

[16] 张雷，黄园淅，程晓凌，杨波，李江苏. 流域开发的生态效应问题初探. 资源科学，2011，33(8)：1422-1430.

[17] 刘丛强，汪福顺，王雨春，王宝利. 河流筑坝拦截的水环境响应——来自地球化学的视角. 长江流域资源与环境，2009，18(4)：384-396.

[18] 毛战坡，杨素珍，王亮，程东升. 磷素在河流生态系统中滞留的研究进展. 水利学报，2015，46(5)：515-524.

[19] Bowes M J, Jarvie H P, Halliday S J, Skeffington R A, Wade A J, Loewenthal M, Gozzard E, Newman J R, Palmer-Felgate E J. Characterising phosphorus and nitrate inputs to a rural river using high-frequency concentration-flow relationships. Science of the Total Environment, 2015, 511: 608-620.

[20] Son J H, Crowley C, Goodwin S, Arabi M, Carlson K H. Relative phosphorus load inputs from wastewater treatment plants in a northern Colorado watershed. Journal of Environmental Quality, 2013, 42(2): 497-506.

[21] Son J H, Goodwin S, Carlson K. Total phosphorus input to the Cache la Poudre River in northern Colorado. Water Environment Research, 2015, 87(2): 169-178.

[22] Jarvie H P, Withers P J A, Hodgkinson R, Bates A, Neal M, Wickham H D, Harman S A, Armstrong L. Influence of rural land use on streamwater nutrients and their ecological significance. Journal of Hydrology, 2008, 350(3/4): 166-186.

[23] Neal C, Jarvie H P, Withers P J A, Whitton B A, Neal M. The strategic significance of wastewater sources to pollutant phosphorus levels in English rivers and to environmental management for rural, agricultural and urban catchments. Science of the Total Environment, 2010, 408(7): 1485-1500.

[24] Bowes M J, Smith J T, Jarvie H P, Neal C, Barden R. Changes in point and diffuse source phosphorus inputs to the River Frome (Dorset, UK) from 1966 to 2006. Science of the Total Environment, 2009, 407(6): 1954-1966.

[25] Jarvie H P, Neal C, Withers P J A. Sewage-effluent phosphorus: a greater risk to river eutrophication than agricultural phosphorus?. Science of the Total Environment, 2006, 360(1/3): 246-253.

[26] Mulholland P J. The importance of in-stream uptake for regulating stream concentrations and outputs of N and P from a forested watershed: evidence from long-term chemistry records for Walker Branch Watershed. Biogeochemistry, 2004, 70(3): 403-426.

[27] Walling D E, Webb B W, Russell M A. Sediment-associated nutrient transport in UK rivers. Freshwater Contamination, 1997, (243): 69-81.

[28] Némery J, Garnier J. Origin and fate of phosphorus in the Seine watershed (France): agricultural and hydrographic P budgets. Journal of Geophysical Research: Biogeosciences, 2007, 112(G3): G03012.

[29] James W F, Larson C E. Phosphorus dynamics and loading in the turbid Minnesota River (USA): controls and recycling potential. Biogeochemistry, 2008, 90(1): 75-92.

[30] Pan G, Krom M D, Zhang M Y, Zhang X W, Wang L J, Dai L C, Sheng Y Q, Mortimer R J G. Impact of suspended inorganic particles on phosphorus cycling in the Yellow River (China). Environmental Science & Technology, 2013, 47(17): 9685-9692.

[31] Maavara T, Parsons C T, Ridenour C, Stojanovic S, Dürr H H, Powley H R, Van Cappellen P. Global phosphorus retention by river damming. Proceedings of the National Academy of Sciences of the United States of America, 2015, 112(51): 15603-15608.

[32] Taoufik M, Dafir J E. A study of water quality in lower Oum Rabiaa basin, Morocco: speciation of nitrogen and phosphorus. Water Quality Research Journal of Canada, 2005, 40(1): 120-129.

[33] Jossette G, Leporcq B, Sanchez N, Philippon. Biogeochemical mass-balances (C, N, P, Si) in three large reservoirs of the Seine Basin (France). Biogeochemistry, 1999, 47(2): 119-146.

[34] Lopez P, Marcé R, Ordoñez J, Urrutia I, Armengol J. Sedimentary phosphorus in a cascade of five reservoirs (Lozoya River, Central Spain). Lake and Reservoir Management, 2009, 25(1): 39-48.

[35] Littlejohn K A, Poganski B H, Kröger R, Ramirez-Avila J J. Effectiveness of low-grade weirs for nutrient removal in an agricultural landscape in the Lower Mississippi Alluvial Valley. Agricultural Water Management, 2014, 131: 79-86.

[36] Sferratore A, Billen G, Garnier J, Smedberg E, Humborg C, Rahm L. Modelling nutrient fluxes from sub-arctic basins: comparison of pristine vs. dammed rivers. Journal of Marine Systems, 2008, 73(3/4): 236-249.

[37] Humborg C, Blomqvist S, Avsan E, Bergensund Y, Smedberg E, Brink J, Mörth C M. Hydrological alterations with river damming in northern Sweden: implications for weathering and river biogeochemistry. Global Biogeochemical Cycles, 2002, 16(3): 12-1-12-13.

[38] Humborg C, Pastuszak M, Aigars J, Siegmund H, Mörth C M, Ittekkot V. Decreased silica land-sea fluxes through damming in the Baltic Sea catchment-significance of particle trapping and hydrological alterations. Biogeochemistry, 2006, 77(2): 265-281.

[39] Medeiros P R P, Knoppers B A, Cavalcante G H, de Souza W F L. Changes in nutrient loads (N, P and Si) in the São Francisco Estuary after the construction of dams. Brazilian Archives of Biology and Technology, 2011, 54(2): 387-397.

[40] Chen N W, Wu Y Q, Wu J Z, Yan X L, Hong H S. Natural and human influences on dissolved silica export from watershed to coast in Southeast China. Journal of Geophysical Research: Biogeosciences, 2014, 119(1): 95-109.

[41] Ouyang W, Hao F H, Song K Y, Zhang X. Cascade dam-induced hydrological disturbance and environmental impact in the upper stream of the Yellow River. Water Resources Management, 2011, 25(3): 913-927.

[42] Zhou J J, Zhang M, Lu P Y. The effect of dams on phosphorus in the middle and lower Yangtze River. Water Resources Research, 2013, 49(6): 3659-3669.

[43] 李亦秋, 鲁春霞, 邓欧, 杨广斌. 猫跳河流域梯级开发的生态效应区域响应. 资源科学, 2011, 33(8): 1454-1461.

[44] Wang F S, Wang B L, Liu C Q, Liu X L, Gao Y, Zhang J, Li S. Changes in nutrient ratios and phytoplankton community structure caused by hydropower development in the Maotiao River, China. Environmental Geochemistry and Health, 2014, 36(3): 595-603.

[45] Némery J, Gratiot N, Doan P T K, Duvert C, Alvarado-Villanueva R, Duwig C. Carbon, nitrogen, phosphorus, and sediment sources and retention in a small eutrophic tropical reservoir. Aquatic Sciences, 2016, 78(1): 171-189.

[46] Vo N X Q, Doan T V, Kang H. Impoundments increase potential for phosphorus retention and remobilization in an urban stream. Environmental Engineering Research, 2014, 19(2): 175-184.
[47] Kim L H, Choi E, Stenstrom M K. Sediment characteristics, phosphorus types and phosphorus release rates between river and lake sediments. Chemosphere, 2003, 50(1): 53-61.
[48] Shin M S, Lee J Y, Kim B, Bae Y J. Long-term variations in water quality in the lower Han River. Journal of Ecology and Field Biology, 2011, 34(1): 31-37.
[49] Novak P A, Chambers J M. Investigation of nutrient thresholds to guide restoration and management of two impounded rivers in south-western Australia. Ecological Engineering, 2014, 68: 116-123.
[50] Avilés A, Niell F X. The control of a small dam in nutrient inputs to a hypertrophic estuary in a mediterranean climate. Water Air, and Soil Pollution, 2007, 180(1/4): 97-108.
[51] Nogueira M G, Ferrareze M, Moreira M L, Gouvêa R M. Phytoplankton assemblages in a reservoir cascade of a large tropical-subtropical river (SE, Brazil). Brazilian Journal of Biology, 2010, 70(S3): 781-793.
[52] 曾辉, 黎小正, 吴祥庆, 庞燕飞, 何安尤, 谢华. 岩滩水电开发对库区水环境的影响. 南方农业学报, 2013, 44(4): 621-626.
[53] 黎慧卉, 刘丛强, 汪福顺, 吴攀, 王宝利, 张翅鹏. 猫跳河流域梯级水库磷的夏季变化特征. 长江流域资源与环境, 2009, 18(4): 368-372.
[54] Tian Y Q, Huang B Q, Yu C C, Chen N W, Hong H S. Dynamics of phytoplankton communities in the Jiangdong Reservoir of Jiulong River, Fujian, South China. Chinese Journal of Oceanology and Limnology, 2014, 32(2): 255-265.
[55] 陈聪聪, 饶拉, 黄金良, 白敏冬. 东南沿海河流-水库系统藻类生长营养盐限制季节变动. 环境科学, 2015, 36(9): 3238-3247.
[56] Liu S M, Hong G H, Zhang J, Ye X W, Jiang X L. Nutrient budgets for large Chinese estuaries. Biogeosciences, 2009, 6(10): 2245-2263.
[57] Thompson P A, Waite A M, McMahon K. Dynamics of a cyanobacterial bloom in a hypereutrophic, stratified weir pool. Marine & Freshwater Research, 2003, 54(1): 27-37.
[58] Dauta A, Lapaquellerie Y, Maillet N. Role of the dams on the River Lot on two types of pollution: point-sources (cadmium) and non-point sources (phosphorus). Hydrobiologia, 1999, 410: 325-329.
[59] Liu Q, Liu S L, Zhao H D, Deng L, Wang C, Zhao Q H, Dong S K. Longitudinal variability of phosphorus fractions in sediments of a Canyon Reservoir due to cascade dam construction: a case study in Lancang River, China. PLoS One, 2013, 8(12): e83329.
[60] Liu Q, Liu S L, Zhao H D, Deng L, Wang C, Zhao Q H, Dong S K. The phosphorus speciations in the sediments up- and down-stream of cascade dams along the middle Lancang River. Chemosphere, 2015, 120: 653-659.
[61] 陈朱虹, 陈能汪, 吴殷琪, 莫琼利, 周兴鹏, 鲁婷, 田蕴. 河流库区沉积物——水界面营养盐及气态氮的释放过程和通量. 环境科学, 2014, 35(9): 3325-3335.
[62] Gabriel O, Balla D, Kalettka T, Maassen S. Sink or source? -The effect of hydrology on phosphorus release in the cultivated riverine wetland Spreewald (Germany). Water Science and Technology, 2008, 58(9): 1813-1822.
[63] Lincheva S, Todorova Y, Topalova Y. Long-term assessment of the self-purification potential of a technologically managed ecosystem: the Middle Iskar cascade. Biotechnology & Biotechnological Equipment, 2014, 28(3): 455-462.
[64] 王华, 逄勇. 藻类生长的水动力学因素影响与数值仿真. 环境科学, 2008, 29(4): 884-889.
[65] Nakamura K. Performance and design of artificial lagoons for controlling diffuse pollution in Lake Kasumigaura, Japan. Ecological Engineering, 2009, 35(1): 141-151.
[66] Jung S W, Kwon O Y, Yun S M, Joo H M, Kang J H, Lee J H. Impacts of dam discharge on river environments and phytoplankton communities in a regulated river system, the lower Han River of South Korea. Journal of Ecology and Environment, 2014, 37(1): 1-11.
[67] Jeong K S, Kim D K, Shin H S, Yoon J D, Kim H W, Joo G J. Impact of summer rainfall on the seasonal water quality variation (chlorophyll a) in the regulated Nakdong River. KSCE Journal of Civil Engineering, 2011, 15(6): 983-994.
[68] Mitrovic S M, Hardwick L, Dorani F. Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. Journal of Plankton Research, 2011, 33(2): 229-241.
[69] Perbiche-Neves G, Ferreira R A R, Nogueira M G. Phytoplankton structure in two contrasting cascade reservoirs (Paranapanema River, Southeast Brazil). Biologia, 2011, 66(6): 967-976.
[70] Webster I T, Sherman B S, Bormans M, Jones G. Management strategies for cyanobacterial blooms in an impounded lowland river. Regulated Rivers: Research & Management, 2000, 16(5): 513-525.
[71] Alrajoula M T, Al Zayed I S, Elagib N A, Hamdi M R. Hydrological, socio-economic and reservoir alterations of Er Roseires Dam in Sudan. Science of the Total Environment, 2016, 566-567: 938-948.
[72] Noh J, Choi H, Lee S. Water quality projection in the Geum River basin in Korea to support integrated basin-wide water resources management. Environmental Earth Sciences, 2015, 73(4): 1745-1756.